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INTEGRATION OF THE PRODUCTION PLANNING AND CONTROL DECISION PROCESS IN A MANUFACTURING ENTERPRISE

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ABSTRACT

The main objective of this paper is to propose and investigate a software architecture framework that facilitates coordination and collaboration among distributed decision entities in a manufacturing facility. Our thesis is that local decisions can benefit from the timely accessibility of appropriately aggregated information about the state of the rest of the manufacturing system. In turn, the manufacturing system as a whole can benefit from the timely dissemination of appropriately aggregated information pertaining to routine decisions or improvements at the various local levels. The *Enterprise Integration* resulting from the concurrent production and control decisions of specialized teams (Autonomous Decision Agents) has the potential to increase overall productivity, quality, and profitability of manufacturing systems.

A hierarchical decomposition and later a functional decomposition approach are employed to identify the autonomous decision agents (for example marketing, strategic management, production planning, scheduling etc.). The communication protocol and the integrating mechanism functions are then established. A planning (what-if analysis) mode is provided for off-line analysis of the system in order to realize concurrent decision making and learning effects. Finally, an on-line asynchronous operation mode is developed for controlling the manufacturing system on a day to day basis.

In addition to relevant software architecture and enterprise integration issues, algorithms and feedback mechanisms will be considered for the particular Operation Planning and Control Activities. Preliminary results from an application to a Semiconductor Testing facility are also reported.

INTRODUCTION

Numerous approaches have been developed in the past for controlling production activities in manufacturing systems but little effort has been applied to the coordination and the integration of the function specific decision tools. As a result, human or computer driven decision agents at different levels of the manufacturing enterprise, pursue their own objectives while desirable synergistic effects on the rest of the system are not realized. In addition, useful feedback information is at best underutilized and the learning process cannot keep pace with the rate of changes in the manufacturing environment. In recent years, the transformation of manufacturing enterprises from monolithic structures to networks of specialized producers, often located far away from each other, has attenuated the need for enterprise integration tools and methodologies. At the same time, affordable on-line information availability and computational tractability become effective means for realizing the benefits of integration.

In the simplest possible abstraction, a manufacturing system receives materials, manufacturing process data and customer requirements as inputs and uses available resources to manufacture products that meet demand. The transformation of inputs to outputs is determined by a set of decisions that are made at different levels of the manufacturing system. These levels can be decomposed either by physical criteria such as location (plants located at different sites, strategic headquarters, distribution network) or by functional criteria (strategic management, marketing, production planning, resource allocation, scheduling and operation). Within each functional team autonomous yet interdependent decision agents transform their own inputs to outputs. Each decision agent has a certain flexibility to process its inputs using alternative methods. The effectiveness of these methods however, cannot be identified in isolation. It can only be deduced from its interaction with the whole system of decision agents.

1 Objectives of the Enterprise Integration Study

Before describing the proposed architecture we should mention in brief the objectives of this study:

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- Facilitate Cooperation between Autonomous Decision Agents by establishing a structured way of interaction.
- Enable agents to evaluate the effect of their decisions on the whole system through *what if* analysis studies by relying on manual or automated software based description of behavior of the other agents.
- Allow improvement of one agent's actions to be utilized by others so that the benefits of improved local decision making propagate and the global potential benefit is fully realized.
- Reinforce the learning process in the system by allowing focused teams to gain intuition on how and why other teams make their decisions.
- Provide communication interfaces with existing legacy Manufacturing System decision tools such as MRP and Shop Floor Tracking
- Achieve flexibility and reusability of the continuously improving decision making Software Infrastructure.

2 The Proposed Architecture

The focus of our effort is to model the interactions across the various decision agents, as well as the decision making process of some of them. In particular, we model extensively the decision making process within the Operations Planning and Control (OPC) framework, while other agents such as marketing, management, process design interact with OPC but their exact decision making process is not modeled in detail. As an example, system specific and efficient scheduling algorithms are developed and employed while demand forecast tools are employed to provide input but are not developed explicitly.

2.1 Decomposition of the Manufacturing System

The manufacturing system can be viewed, according to the order that basic inputs and goals are specified, as a hierarchy of intercommunicating decision levels. These levels are:

L1. The Executive Level
L2. The Production Planning Level
L3. The Stochastic Analysis and Performance Evaluation Level
L4. The Scheduling Level
L5. The Operational Level

The main focus is to model in detail the interaction between all 5 levels and the decision making process in levels L2, L3 and L4. Figure 1, shows the information flow and exchange across decision levels. Figures 1 through 4 are shown on pages 3 and 4.

At each level of the hierarchy there are more than one decision agents (ADAs). ADAs at level i receive information from ADAs at level i-1 and i+1 and from cooperating ADAs at level i. It is possible, though not common, that ADAs at non-adjacent levels also communicate directly. An ADA has known inputs and outputs. Therefore, its behavior is constrained by a fixed set of rules and its invariant properties. For example, a scheduling ADA cannot specify product demand or design and must always provide information on machine loading priorities. A typical breakdown of the hierarchy levels into autonomous decision agents is shown in Figure 2.

The directional arrows show the flow of information, while the labels next to them refer to the level and the information element shown in Figure 1. For example, 2.4 refers to the fourth information set of the second level (in Figure 1 is shown to be the Long Term Capacity Allocation information).

Each ADA is modeled based on four basic concepts: inputs, outputs, control parameters and functions [3],[4]. An example is the finite capacity scheduling ADA shown in Figure 3.

2.2 Modes of Operation

In order to accomplish the necessary objectives four modes of operation have to be implemented. These are:

2.2.1 The System Data Modeling and Manipulation Mode

In this mode the information that is relevant to the manufacturing system of interest is identified and modeled in an object oriented fashion. Examples of generic manufacturing objects are part types, machine groups, resource availability patterns etc. The complete list of objects and their attributes are identified and stored in a common database accessible by all decision agents.

2.2.2 ADA Configuration Mode

In this mode we identify the decision agents needed to process information associated with different characteristic time scales, locations and functions and also the information they should exchange. For each ADA, the necessary inputs and outputs, the possible methodologies or functions to be employed and the necessary control parameters are identified. An ADA's function can be either a computer program, which receives control parameters from a human, and input data from an object oriented database, or simply a human that decides with the help of some simple (visual) decision support. In the case of computer driven agents the necessary input and output formats are determined and the functions for converting data from database objects to input files and vice versa are created.

2.2.3 Planning (or What If Analysis) Mode

After the system and the interaction process have been defined for a manufacturing system we proceed to the analysis mode. In this mode the software system is used in an off-line fashion to evaluate possible scenarios and determine good planning decisions or choices at some local level by considering interaction effects with other system local levels.

2.2.4 The Asynchronous Operation Mode

Finally, the software tool can be used on-line by actual manufacturing teams to control day to day operations. Agents should be able to communicate and exchange their output through a network. Information from inside and outside the production floor will thus be processed and fed back to agents.

The following 4 figures describe visually the proposed architecture. Figure 4 shows the aggregate system architecture after defining the four modes.

As Figure 4 shows, careful consideration of the manufacturing system is followed by the implementation of the data model and ADA configuration modes. The data model focuses on the physical data while the ADA configuration focuses on the decision making process. We proceed next to the planning mode. Before a new study is initiated a temporary common database is created and the software interface accesses it during each planning study in a blackboard system fashion [2]. After the integration controller and the information services modules are operational, planning studies can be performed to determine the best possible way for controlling the manufacturing system. Off-line planning enables decision agents to achieve expertise and decide on a coordinated strategy. This information is passed on to the asynchronous system operation mode which is used to control the manufacturing system in a real time fashion. This completes the cycle of the Enterprise Integration effort.

In order to be effective, modes 1 and 2 must be flexible and non restrictive, allowing different manufacturing systems to be modeled rapidly. This will allow manufacturing experts to focus their effort on mode 3 (i.e. the off-line, low cost determination of a good operating and coordination policy). Enterprise integration can eliminate the complexity and chaos encountered often in factory operations that are not coordinated effectively. Knowledge, stability and anticipation of dynamic effects under enterprise integration allows operators and managers of everyday activities in the asynchronous operation mode to operate the system in an orderly and stable fashion and thus focus their efforts on providing constructive input and suggestions rather than on "firefighting".

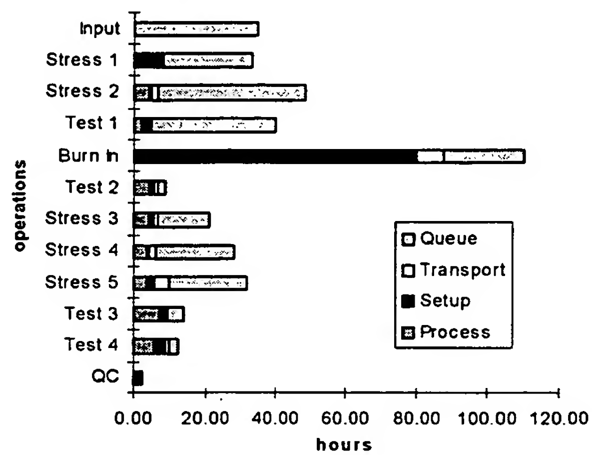
3 INDUSTRIAL IMPLEMENTATION

The proposed architecture is elaborated through a case study on a one-part type IC testing facility. Because the part type produced is a relatively new design and since it is used for airbag operation, testing has to be performed on every single IC. As it is common with new designs there are low yields and a lot of unexpected machine failures. The strategic objectives are primarily to maximize throughput and also to cut down cycle times. Various production system configurations were designed and evaluated leading to performance improvements.

Work enters the system in the form of untested ICs. The ICs are batched in lots and proceed through a set of environmental stresses and tests. Stresses include Burn-In, environmental, solder dipping etc. while tests are performed at different temperatures.. Some resources are batch resources, i.e. they can load many lots at once and have specific loading times. Figure 5 shows the sequence of operations and the breakdown of average cycle time of lots. The Burn In operation is a batch operation that has a standard process time of 80 hours which appears as setup because it is independent of the lot size.

High uncertainty levels, reentrant flow and the mix of very short and very long processing times make the system very challenging and raise a lot of interesting control issues.

Figure 5: Operation Sequence and Average Cycle Time Breakdown



3.1 Design of the Enterprise Integration Framework

The following ADAs were considered in the hierarchical framework of the enterprise integration effort for this facility:

3.1.1 Marketing ADA (Executive Level)

Inputs:
From strategic management: business strategy.
From lower levels (feedback): product specific cycle time trends, expected delivery dates, safety stocks).
Outputs:
Product Specific Demand patterns.
Short term customer orders and delivery requirements.
Functions:
Simple analytic estimation function of part type i demand over time.

3.1.2 The Production Planning ADA (Planning Level)

Inputs:
From Marketing: Demand allocated to each factory section.
From Capacity Planning: Long term capacity availability.
From Process Engineering: Yield and uncertainty information.
Outputs:
Capacity feasibility check and expected utilization information.
Lot size optimization and lot cycle time prediction.
Functions:
Capacity evaluation for specific lot sizes selected. Problem simplifies since all lots have same size.

3.1.3 The Capacity Allocation ADA (Planning Level)

Inputs:
From Marketing: Demand allocated to each factory section.
From Strategic Management: Resource acquisition plans.
From Production Planning: Average expected utilization for required product mix. Bottleneck identification and resource specific utilization from scheduling.

From Scheduling (feedback): Expected detailed utilization of resources. Identification of exact time and location of bottlenecks.

Outputs:

Allocation of machines and labor to competing sections.

Allocation of dedicated machines to setup intensive operations.

Functions:

Manual decisions for long term capacity allocation.

Shift by shift reallocation of labor for short term allocation.

3.1.4 The Material Requirements Planning ADA (Planning Level)

Inputs:

From Production Planning: Selected lot size. Expected lot cycle Time.

From Scheduling (feedback): Revised expected cycle times.

From lower levels: (optimal lot sizes and corresponding expected lead times, lead time variability and queuing results).

Outputs:

Earliest release time of raw materials.

Functions:

MRP generic software including feedback (reevaluation) mode.

3.1.5 The Scheduling ADA (Scheduling Level)

Inputs:

From MRP: Raw Material earliest release times

From Capacity Allocation: Resource availability

From Marketing: Required delivery dates for each product

Outputs:

Priorities for each resource cell.

Variability of cycle times due to production mix effects and priority determination.

Expected utilization of each resource on a shift or even hourly basis.

Expected Delivery dates of planned work..

Expected WIP status of the system in the future.

Functions:

Dispatch Rules. Sophisticated scheduling such as Lagrangian Relaxation does not outperform local dispatch rules for this simple one part type system.

3.1.6 The Shop Floor Tracking ADA

Inputs:

From shop floor observation: information on completion and start of operations.

Outputs:

status and exact location of WIP

Functions:

Future WIP status can be immediately determined either by the proposed schedule or by actual system operation.

The above is a list of all the currently active ADAs that were modeled in the enterprise integration framework implementation for the semiconductor testing facility. Two more ADAs the Strategic Management and the Financial Planning/Accounting ADA were actively incorporated in the study but their detailed description is beyond the scope of this paper. Other ADAs, that are not implemented yet, will be included in the future in order to enrich the model and empower the user to make better decisions. Some of the ADAs that will be incorporated in later versions include the following:

The Performance Evaluation ADA which generates average WIP estimates during different time periods.

The Hedging Level Design ADA which can be employed to determine hedging due dates, [1] (i.e. due dates shifted earlier to safeguard against uncertainty induced tardiness).

The Group Technology ADA that can be used to allocate dedicated machines to setup intensive operations.

In addition, simulation and better scheduling practices are tools that will be incorporated upon further evaluation of the scheduling and uncertainty issues.

3.2 Results from the Semiconductor Testing Facility

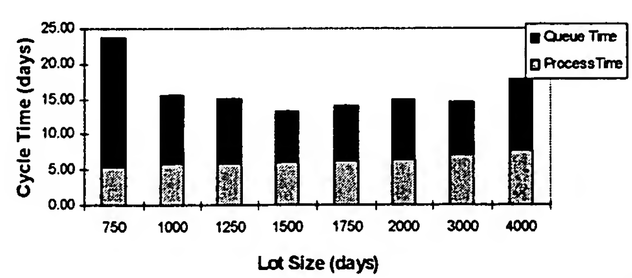
The following case studies were completed sequentially. At each step new knowledge was gained and used to improve the operation of the system. Conclusions and optimal results obtained from previous steps were used to advantage in later steps. Particular emphasis is given to the policy improvements resulting from the cooperation of two or more agents.

3.2.1 Selecting an Optimal Lot Size

The first case study was designed to determine an optimal lot size. After Marketing, Financial Modeling, and Capacity Allocation ADAs provided the input parameters the Production Planning ADA was employed to estimate cycle times and average resource utilization for different lot sizes. This information was passed to MRP which determined input material release. Following that, a scheduling algorithm was invoked to determine actual performance measures. Finally results were fed back to the financial ADA for a system evaluation.

A reasonable demand rate, that satisfied customer needs at this point of time, was determined to be 10,000 ICs per week. Because of low yields, 24,000 ICs have to be released in the system to achieve an output of 10,000. In the Production Planning ADA, different lot sizes, varying from 500 to 4000 ICs per job were evaluated to determine the one that provides the best cycle time. As Figure 6 shows the smallest cycle time was observed for a lot size of 1500 ICs.

Figure 6: Breakdown of Cycle Time for Different Lot Sizes



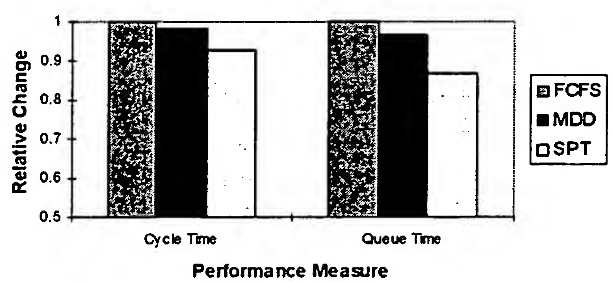
For lot sizes smaller than 1500, setup change frequency increases significantly and therefore resource utilization and queue times increase as well. On the other hand, when lot sizes exceed 1500 the required processing time per lot increases and as a consequence the total process as well as queuing time increase as well. Cycle time does not increase monotonically with lot size due to the fact that the Burn-In oven's capacity is better utilized for some specific lot sizes due to divisibility limitations.

This part of the study demonstrated a useful concept, rather trivial but not clear to many production managers. There is an optimal lot size to be found on any production floor and the simple notion that "*the smaller the lot size the better*" is usually wrong, in the presence of setups. After selecting the best lot size we proceeded to the next part of the study.

3.2.2 Selecting the Best Scheduling Rule

For the purposes of this system simple heuristic dispatch rules were used. This is because there is only one part type and jobs do not correspond to specific customer orders but to cumulative demand. The following three dispatch rules were tested. First Come First Serve (FCFS), Modified Due Date (MDD) and Shortest Process Time First (SPT).

Figure 7: Effect of Scheduling Rule

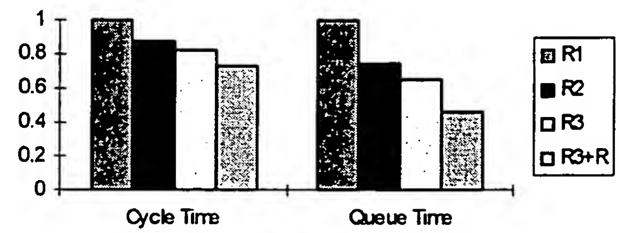


The Shortest Process Time First rule, provided the best results and it was used for the remainder of the case study.

3.2.3 Modifying Routing and Invoking Cooperation between MRP and Scheduling

In this part of the study alternative routes were assumed and their effect on cycle times determined. As it can be seen from Figure 5 a great percentage of queuing time occurs before the Burn-In operation. This is because the Burn-In oven can fire (load) only on three specific week shifts and jobs that arrive at it at any other time may wait for a long period (case R1 in Figure 8). To avoid this situation the Burn-In operation was moved on the beginning of the route and became the first operation (case R3 in Figure 8). A second similar route was tested where branding became now the 5th instead of the 2nd operation (case R2 in Figure 8). The best result was observed for case R3. Nevertheless, queuing time of jobs in the input buffer did not decrease significantly. To reduce the expected queue time on the input buffer a new release policy which coordinated release of material with the Burn-In oven's firing times was implemented (case R3+R in Figure 8). As expected, queue time and as a consequence cycle time were reduced further.

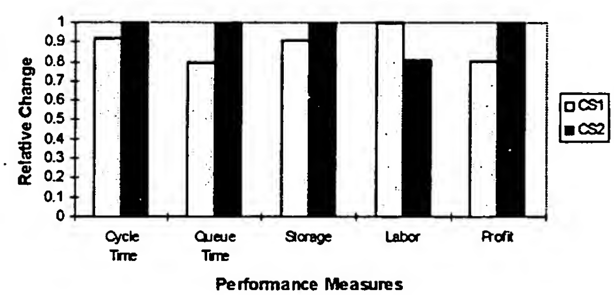
Figure 8: Effect of Routing Changes and MRP-Scheduling Coordination



3.2.4 Reducing Capacity at Non-Bottleneck Stations

After looking at the utilization of the resources we observed that one of the machine groups was utilized only 30% of the time. That was the machine group for the first operation. As Figure 9 shows the final net benefit function has a strong coupling to the labor costs. Consequently, a reasonable approach would be to reduce capacity at this station.

Figure 9: Effect of Reducing Capacity

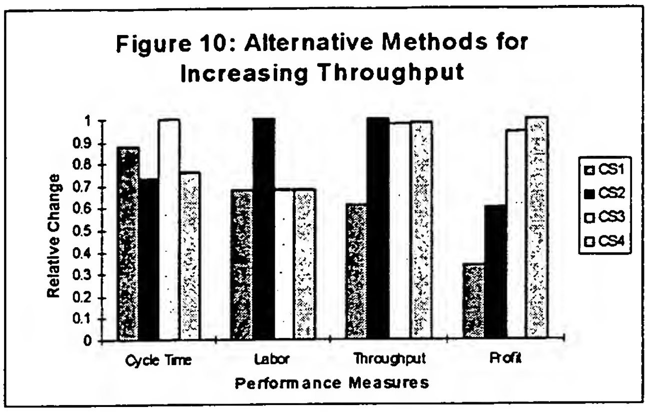


Capacity was reduced and cycle time increased by a small amount. The additional costs from the increase of cycle time were smaller than the benefit obtained from reducing labor costs, therefore the action improved the overall benefit. This was true for the particular unit costs that were applicable to this system and one should notice that a different cost ratio could have made this decision undesirable.

3.2.5 Alternative methods for increasing throughput

Assuming that the strategic objective of management was to increase throughput, three possible cases were considered and the results appear in Figure 10. Case CS1 is the basic best case obtained so far yielding a throughput of 10,000 units per week. In case CS2 a new tester is acquired and labor added to all stations so that they are now available throughout the week. As a result throughput increased to 16,000 units but labor costs increased also. In case CS3 no additional capacity was added but yields of the testing operation improved, by initiating a

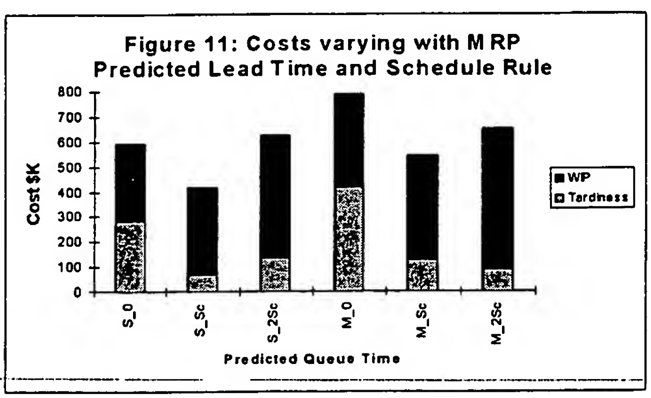
process and product improvement project. As a result much less WIP was now necessary to obtain the desired throughput of 16,000 units.



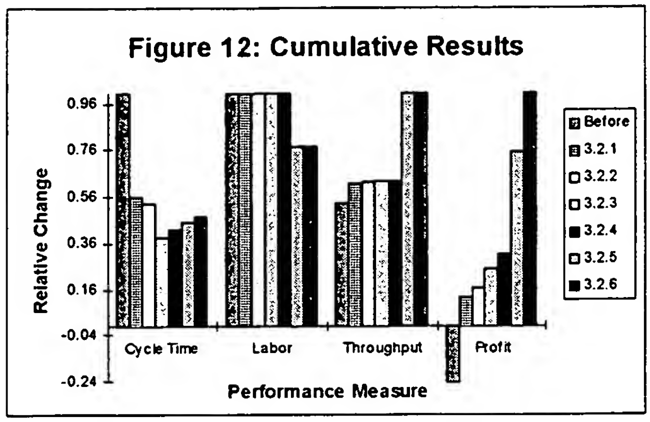
As Figure 10 shows, case CS3 resulted in considerably higher profit margins and should be adopted. Finally, the effect of reducing the long time of the Burn-In operation from 80 to 24 hours is examined. This kind of analysis is very helpful in terms of determining what actions or improvement projects will provide the biggest benefit for the production floor. Since there are hidden and fixed costs behind any such project (buy a machine, deploy specialized engineers to work on process improvement projects) it is necessary that strategic management has a clear view of the expected benefits and tradeoffs before it decides on a specific action.

3.2.6 Employing feedback between MRP and Scheduling

In this case study we examined the effect of feedback from scheduling to MRP for two different scheduling rules (MDD and SPT, denoted as M and S respectively in Figure 11). Initially MRP has no information about scheduling and assumes that queue time will be zero (denoted as _0). After a schedule is calculated, we rerun MRP and release lots based on the assumption that queue time will be equal to what the schedule predicted (denoted as _Sc). The case of overestimating lead times is also examined (_2Sc). The results show that a combination of SPT scheduling rule and release of material based on the correct queue times reduces costs significantly.



Finally, Figure 12, shows the cumulative results obtained.



CONCLUSION

The proposed enterprise integration framework was shown in a substantive case study to result in a continuous improvement of the desired objectives. While optimization of a specific ADA's actions may not yield dramatic improvement in isolation, use of local improvement information by collaborating ADAs may bring about significant additional system wide benefits.

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